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14. ABSTRACT

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COMPOSITE DAMAGE DETECTION USING A NOVEL ULTRASONIC METHOD

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ABSTRACT

The nondestructive evaluation (NDE) of complex composite structures often requires labor intensive, expensive methods due to multiple failure modes, difficulty detecting damage, and the large scale of the structures. Conventional NDE methods have been successful but can be improved by incorporating ideas from other fields. In this work, the technology developed in the infrared camera industry is used and incorporated into an ultrasound system to produce an inspection tool with a wide field of view that displays video images of damage in composite structures in real time. Benefits are higher sensitivity, increased inspection speed, and intuitive interpretation of results.

INTRODUCTION

Improvements in manufacturing reliability will have rewards proportional to the cost of the item, the number of items produced, and the probability of a defect in a single item. High payoffs exist whenever there are any advancements inspection capability for solid rocket motors (SRM's), whether during the actual manufacturing process itself, or afterwards during storage or handling. These are high payoffs because potential failure threatens life and property and because of the high cost of the hardware and its payload. Although industry has improved the production of solid rocket motors, the motors still contain defects and may be damaged during handling or storage. If we can improve the methods by which we inspect solid rocket motors during manufacturing and after production, the result will be improved reliability and reduced cost.

Strategies for improved reliability include health monitoring systems, live testing of stockpile ordnance, and nondestructive evaluation. NDE is very useful because it can be applied to existing systems and no motors are sacrificed. High reliability is ensured by using multiple methods of nondestructive evaluation, for example, X-ray methods and ultrasonics may be used as inspection tools. Advantages specific to ultrasonics include subsurface flaw detection and automation capability. One disadvantage is that the use of transducers produces point-wise data that makes full inspection of a large SRM tedious. Additionally, there may be impedance mismatch problems as the ultrasound wave attempts to travel through different layers of very dissimilar materials (for example, through a metal case into a rubber layer). The presence of thin layers also may give multiple reverberations that are hard to distinguish from each other. Another issue is whether the waves can penetrate into the SRM materials (especially the propellant) without loss of signal due to dispersion within the material. [1]

In this paper, we introduce an innovative ultrasonic method that is flexible and adaptable. The time integration of ultrasonic signals improves the sensitivity of the system and solves problems with penetration of dispersive materials. The improved field of view greatly improves the speed of ultrasonic inspections. This new method is useful to the SRM industry in general (both government and industry), but will also be useful in many other commercial sectors.

PROBLEM STATEMENT

We have already mentioned some difficulties associated with inspection of solid rocket motors. The Air Force was looking for an easy to use, portable inspection system that could be used with existing munitions. However, the most important desired attribute was flexibility because the number of materials used in the motor and their dissimilarity gives rise to a multitude of inspection scenarios.

For example, frequently the inspection method must be able to penetrate an external cork insulation layer. This layer has properties substantially different from the underlying case. Also, the cork layer may separate from the case and the debonds need to be detected and characterized. The case material may be either metal or composite, but composites are being used increasingly due to improvements in performance and reductions in cost. However, composites are more difficult to inspect, may have multiple modes of damage (e.g., delaminations, fiber breakage, matrix damage), and may have hard to spot impact damage. Within the case are multiple layers of additional materials that may contain defects. An insulation layer and a rubber liner layer are also present, as well as a thick layer of a highly filled polymer (the propellant). Delaminations may occur between any of these layers and can be critical defects that must be detected and quantified. [2]

Because of the multiple requirements, several means of inspection are required. Any system that could improve one or more of these inspection processes and that could work on existing ordnance would be desirable. Flexibility in a system would allow for more than one of these issues to be addressed. Cost effectiveness is also an issue if the SRM industry is to embrace the new technology. The innovation in ultrasonic methods described here uses the fusion of two technological areas to produce a flex-

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ible system that is cost effective and easy to use with solid rocket motor components.

EXPERIMENTAL APPARATUS

Frequently a significant innovation is made by taking two separate ideas and combining them to form a new capability. An obvious example is snowboarding, which incorporates skateboarding and snow skiing features. A more technical example is vertical take-off and landing aircraft, which incorporates ideas from rotary and fixed wing aircraft to produce a new vehicle with both efficient forward propulsion and ability to land in small facilities. The ultrasonic system introduced here is a fusion of infrared camera and ultrasonics technologies, and solves several problems found with conventional ultrasonics.

Infrared cameras make use of two-dimensional arrays of sensors that integrate the effects of exposure to light over a certain time frame. This is a key feature of the ultrasonic system developed here, which uses a single piece of piezoelectric material applied to a conventional infrared two-dimensional array. The most important improvement when using such an array is that it enlarges the field of view of the system, making scanning of large objects much faster. Also, for this system the ability of each element on the chip to integrate the signal over the time span of a video frame (33 ms) greatly improves the signal-to-noise ratio (S/N ratio) of the system, making it possible to see into more dispersive materials and/or to find smaller defects in materials under inspection. An additional benefit is that intuitive interpretation is possible, since ultrasonic waves create voltages that are recorded as gray scale video images. This reduces cost and improves system reliability further through reductions in personnel requirements and training. Finally, the piezoelectric material is sensitive to a wide range of ultrasonic frequencies (250 kHz to 15 MHz), so that changing frequencies can be accomplished merely by swapping ultrasonic source transducers. The current setup uses an array of 120x120 pixels (14,400 pixels per image) embedded onto a chip that is 1 cm wide (see Fig. 1). The piezoelectric material is PVDF and is manufactured with a poling technique; the process makes the material sensitive to ultrasonic perturbations while minimizing "cross-talk" between the array elements. Future chips will incorporate preamplifiers and peak detectors for each element. [3–10]

The ultrasonic camera is part of the system depicted in Fig. 2; other subsystems include the acoustic lens system and the ultrasonic transmitter. This transmitter is a large-area unfocused transducer that produces a collimated plane wave that penetrates the object (in this case a solid rocket motor consisting of different layers of dissimilar materials). Because of the dispersive nature of the materials, a low frequency was chosen (1 MHz). The low frequency penetrates the materials but with an associated wavelength that can still detect small defects. The wave is scattered by defects in the material and the affected wave containing information on the location and size of the defects is then focused by the acoustic lens system. This consists of three lenses machined from polystyrene: a large (127 mm diameter) field lens positioned close to the target and two smaller focusing lenses (76.2 mm diameter) mounted close to the array. The two smaller lenses move in tandem to provide focusing. The field of view for the system is 76.2 mm. [11]

Currently, the system has been tested in through-transmission mode and in pulse-echo mode in a water tank (shown in Fig. 3). In the final version, each of the subsystems (transmitter, receiver, and focusing lens) will be incorporated into a portable unit that operates in pulse-echo mode, allowing us to inspect motors from the external surface (see Fig. 4). Water coupling of the system and inspection part will be accomplished using a weep system. [11]

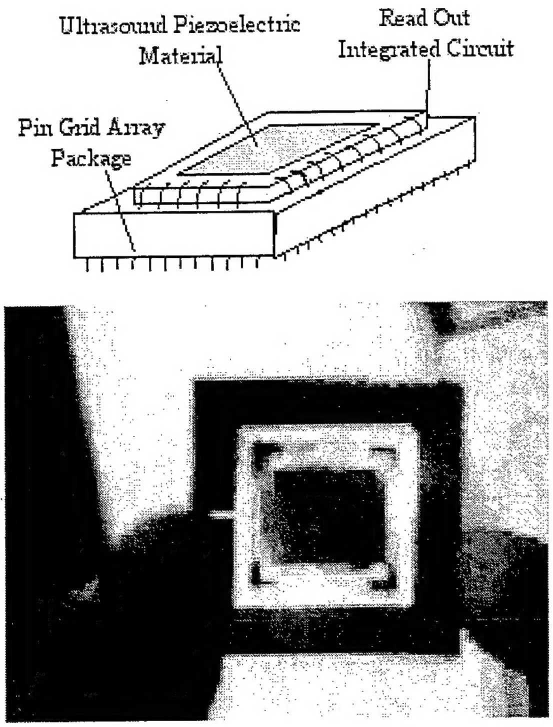

Figure 1: Two-Dimensional Ultrasonic Sensitive CMOS Array

RESULTS

Currently the system is being used in through-transmission mode and in pulse-echo mode to study impact damage and delaminations in solid rocket motor specimens. Typical specimens are 203.2 mm by 203.2 mm with 6.35 mm of graphite-epoxy composite motor case and 6.35 mm of rubber liner layer. Impact was introduced using a calibrated impact system and produces damaged regions 25.4 mm in diameter. Figure 5 shows the images from the system. These images are available in real time and are recorded onto videotape for later retrieval. In Fig. 5, the left image is a defect free zone and the right image is a 25.4 mm diameter delamination in the case material in a graphite-epoxy case/rubber liner specimen.

Additional results show the ability to discern impact damage in honeycomb specimens (Fig. 6) and the ability to use gating techniques to change the depth examined and the depth of field. The minimum detectable defect size depends on the frequency (and hence the wavelength) of the transmitter used. At 5 MHz (the frequency used for the composite in Fig. 6) the defect resolution capability was 0.5 mm, but at the 1 MHz frequency it is 2.5 mm.

SUMMARY AND CONCLUSIONS

A new ultrasonic inspection system is being developed and adapted to the requirements of the solid rocket motor industry. The system uses infrared camera technology as a key innovation, resulting in a flexible system. Key advantages are large field of view, intuitive real-time interpretation of results, and higher signal to noise ratio. The system has been tested with solid rocket motor components including graphite epoxy motor cases and

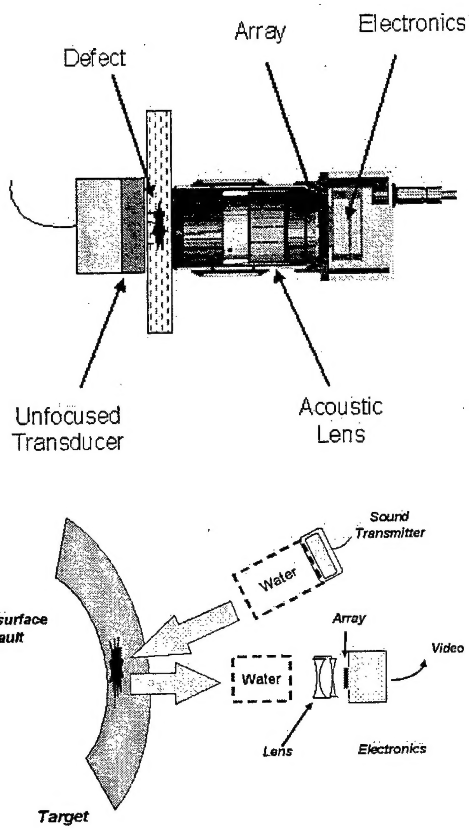

Figure 2: Schematic of Complete Ultrasonic System in Both Through-Transmission and Pulse-Echo Mode

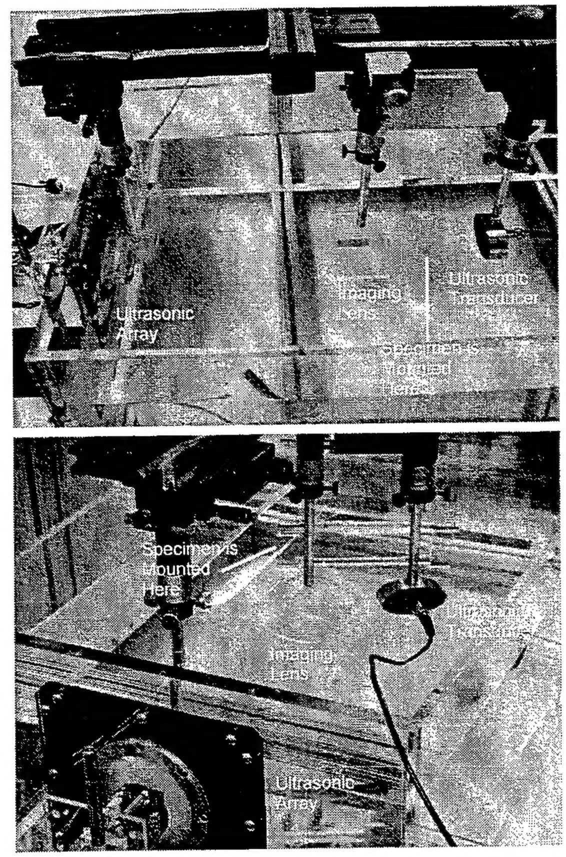

Figure 3: Experimental Setup for Ultrasonic NDE System Using Through-Transmission and Pulse-Echo Modes

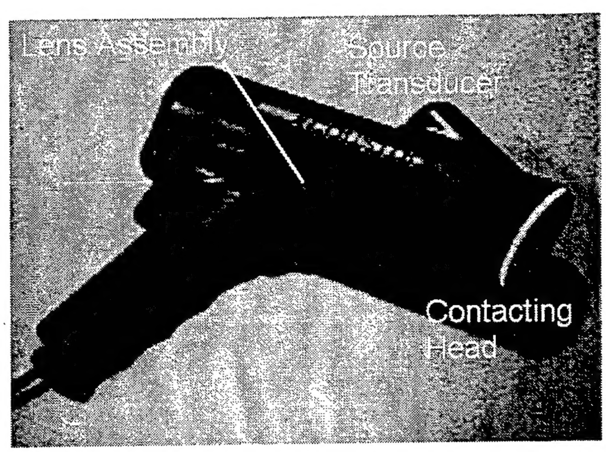

Figure 4: Prototype of Portable Version of Ultrasonic System

has successfully found impact damage in these cases. The system also inspects honeycomb composites and can find defects in these composites. Other possible uses being investigated are the detection of debonds in the composite case-rubber liner layer, real-time recording of damage evolution in propellants during tensile testing. Future improvements include incorporation into a portable unit. Other commercial sectors may benefit, as the unit could be used for subsurface defect detection in piping, pressure vessel, and semiconductor industries. The medical imaging industry would also be able to make use of the system. Vascular, muscular, and skeletal imaging is possible without speckle effects prevalent in current systems.

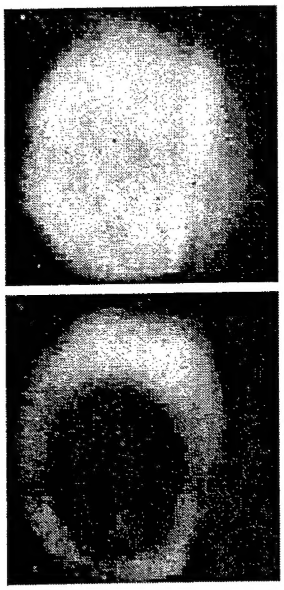

Figure 5: Defect-Free and Impact Damaged Region in Graphite Epoxy Motor Case Specimen

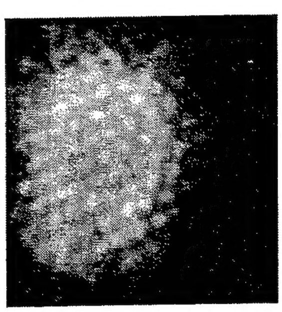

Figure 6: One-Inch Field of View of Honeycomb Composite Specimen

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[2] VanderHeiden, Burt and Pearson, Lee. Personal Communication (July 2002). Alliant Techsystems, Magna, Utah.

[3] Lasser, M. and Harrison, G. A Novel High Speed, High Resolution Ultrasound Imaging System. In QNDE Review of Progress in Quantitative NDE, volume 17B, pages 1713–1719. Plenum Press (1997).

[4] Lasser, M., Lasser, B., Kula, J., and Rohrer, G. Latest Developments in Real-Time 2D Ultrasound Inspection for Aging Aircraft. In 10th Annual AeroMat Conference and Exposition (1999). OK

[5] Lasser, M., Lasser, B., Kula, J., and Rohrer, G. On-Line, Large Area Ultrasonic Imaging for Composite Manufacturing. In American Society for Nondestructive Testing Conference (1999). OK

[6] Lasser, M. A Novel High Speed, High Resolution Ultrasound Imaging System. In ASNT Fall Conference: NDT - Keystone of Quality, pages 196–198. ASNT (1997).

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[9] Lasser, M. and Kula, J. Real-Time, High Resolution, Ultrasound C-Scan Imaging System. In Non-Destructive Evaluation Techniques for Aging Infrastructure and Manufacturing (1998).

[10] Lasser, M., Harrison, G., and Kula, J. Real-Time, Depth Sensitive C-scan Imaging System. In 7th Annual Research Symposium Transfer of Emerging NDE Technologies (1998).

[11] Lasser, Robert. Personal Communication (October 2002). Imperium, Inc., Silver Spring, Maryland.

Composite Damage Detection Using a Novel Ultrasonic Method

Presented at the Society for Experimental Mechanics Spring Conference

Charlotte, North Carolina, June 2-4, 2003

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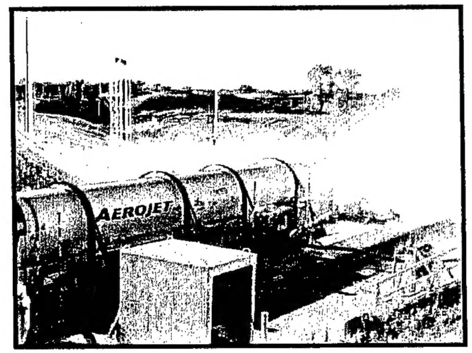
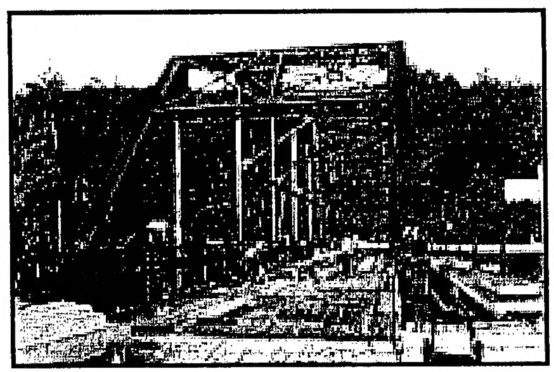
Introduction

Consequences of Failure

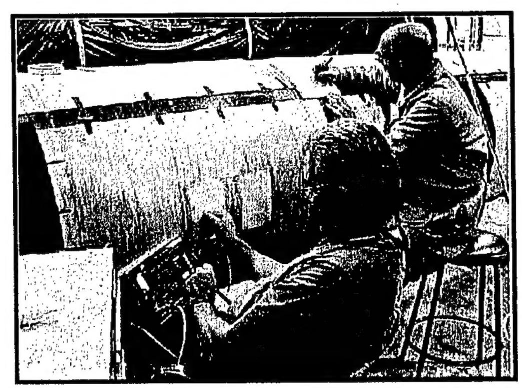
Ways to Ensure Reliability



Live Testing

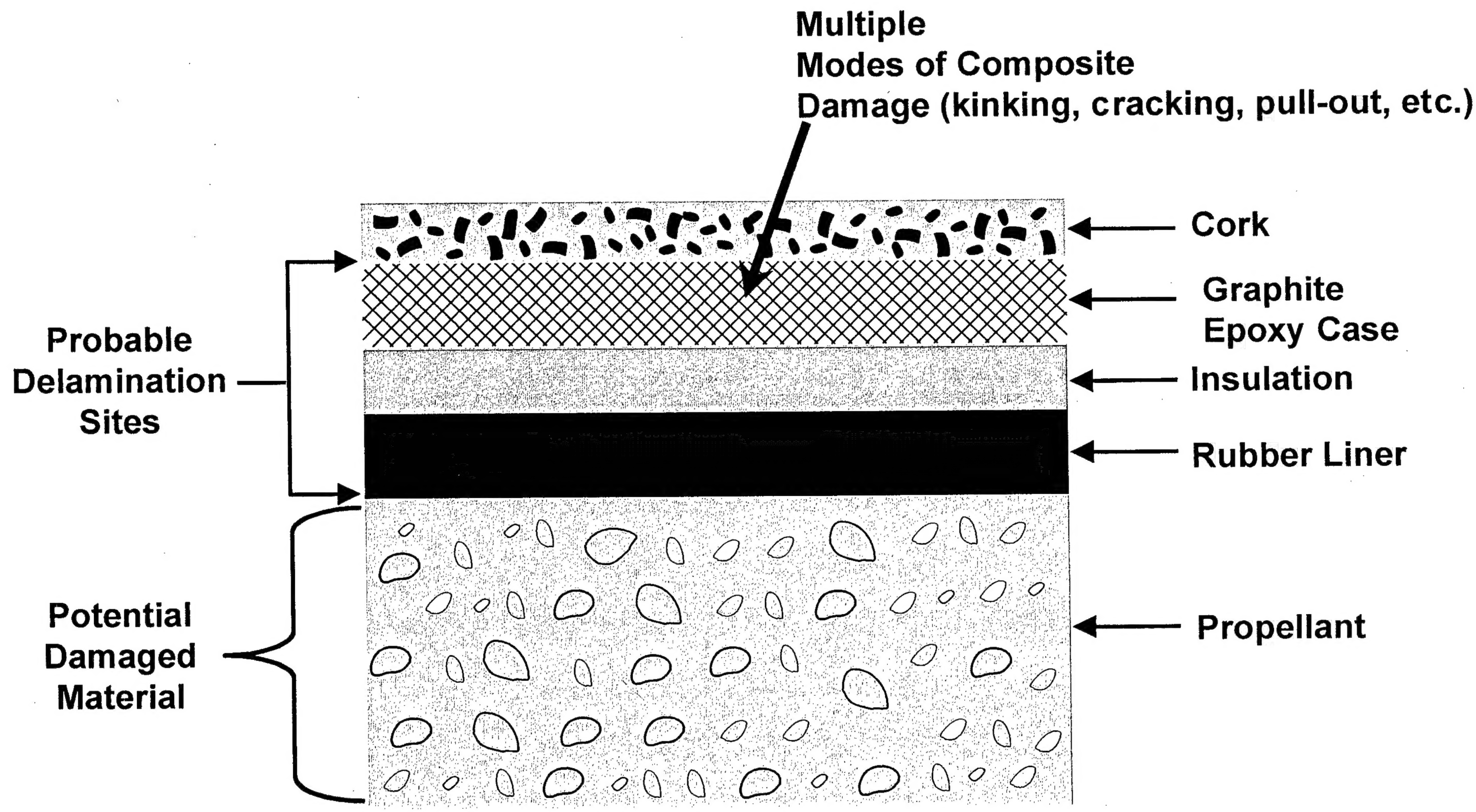


Health Monitoring



Nondestructive Evaluation

Flexibility Important

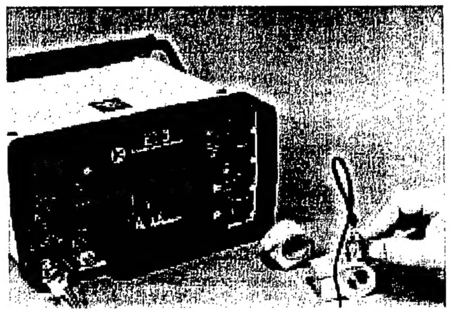


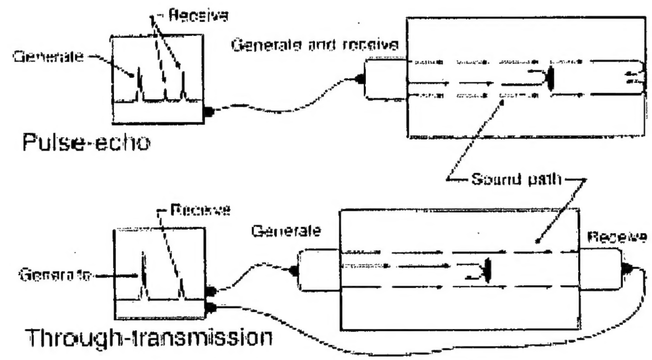
Preliminary Design Objectives

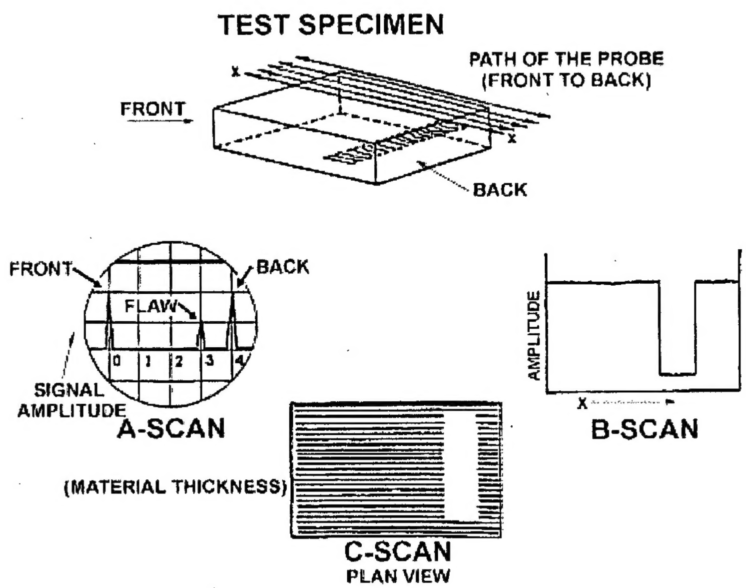
Impact damage in GEM, 76.2 mm FOV, liner delaminations (optional)

1. Integrate I300 for motor casing:
2. Implement 76.2 mm field of view
3. Expand operating frequency (0.5 MHz to 5 MHz)
4. Sample construction
5. Design motor case coupling mechanism
6. Performance Evaluation

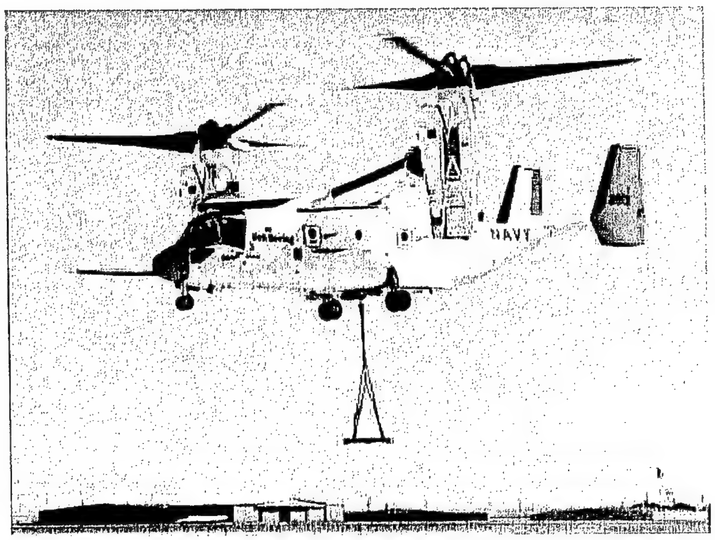
Conventional Ultrasonics



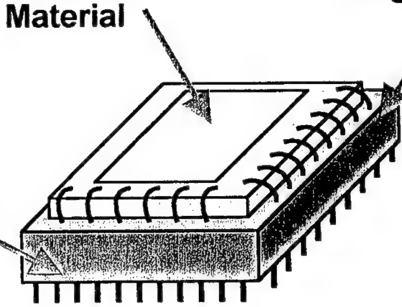


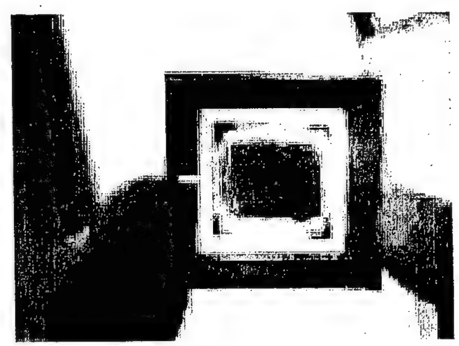


Experimental Apparatus



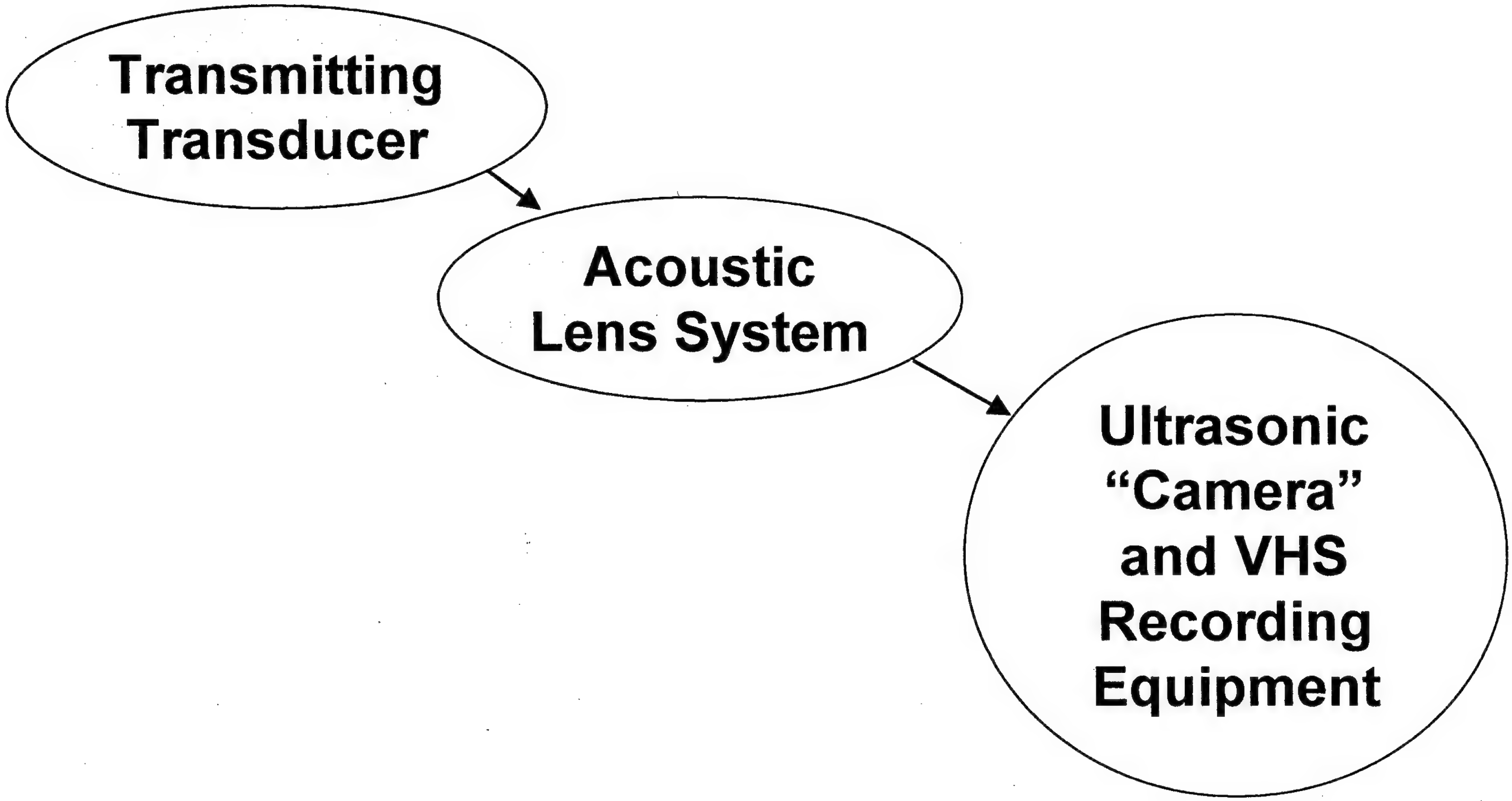
Osprey from Helicopter and Fixed Wing Airplane Technologies





Ultrasonic “Camera” from Infrared Camera and Ultrasonic NDE Technologies

Experimental Apparatus – Three Separate Subsystems



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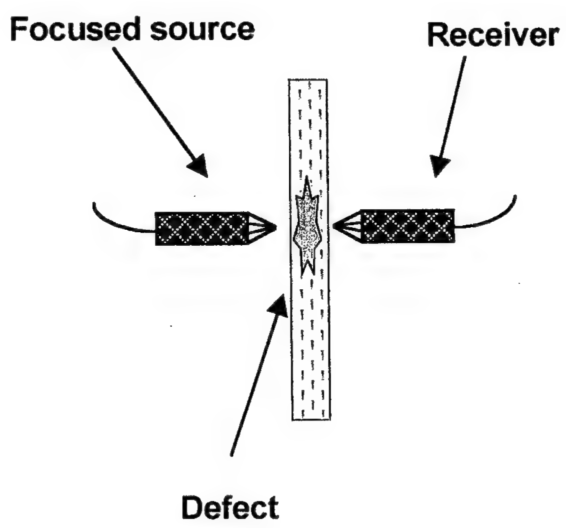
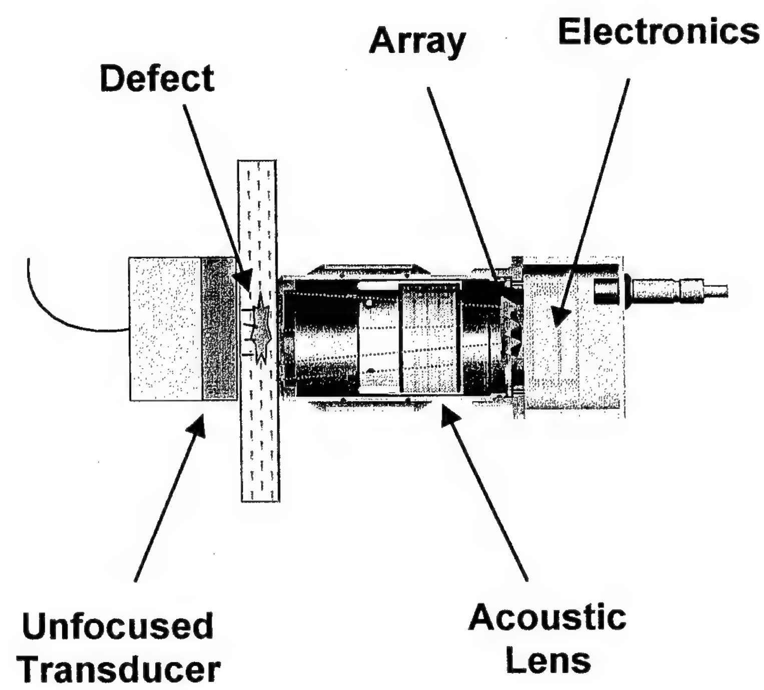
System Schematic – Through Transmission





Conventional Point By Point Scanning: 1 point

DAV Large Area Scanning: 14,400 points

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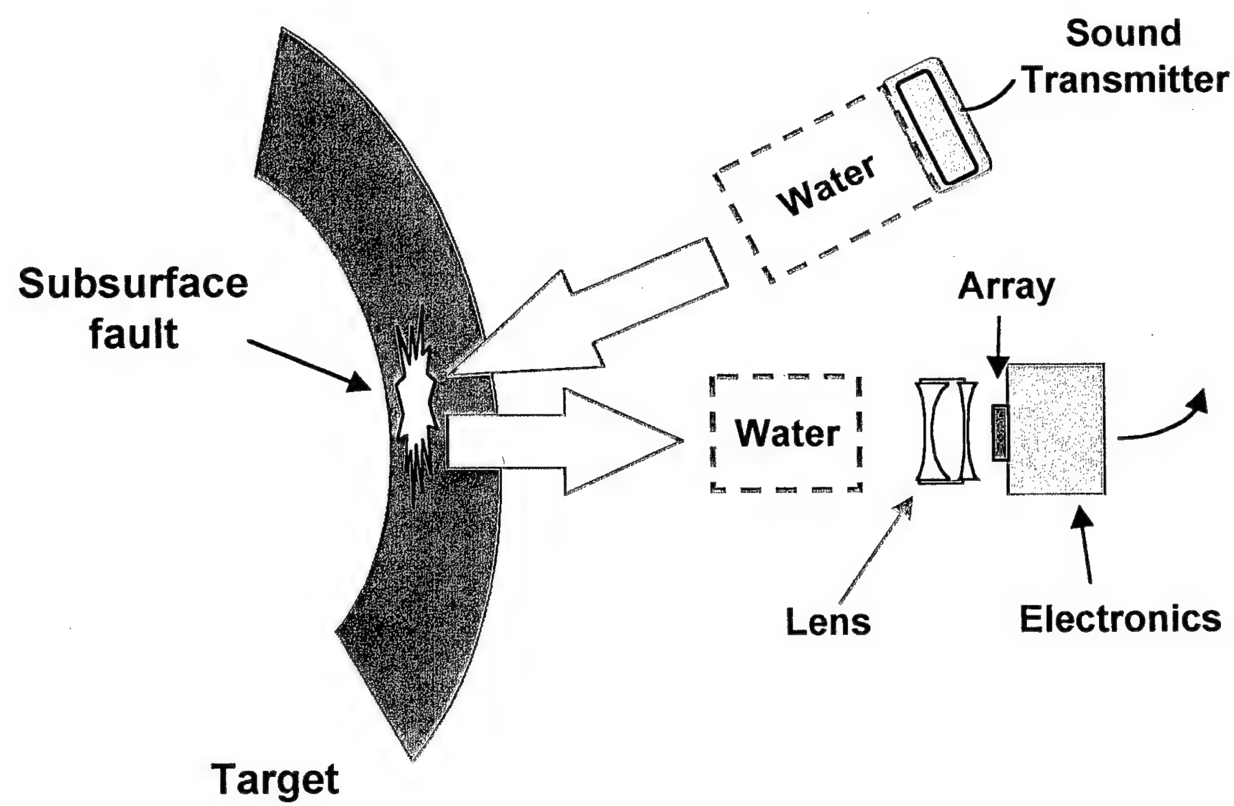
System Schematic – Pulse-Echo



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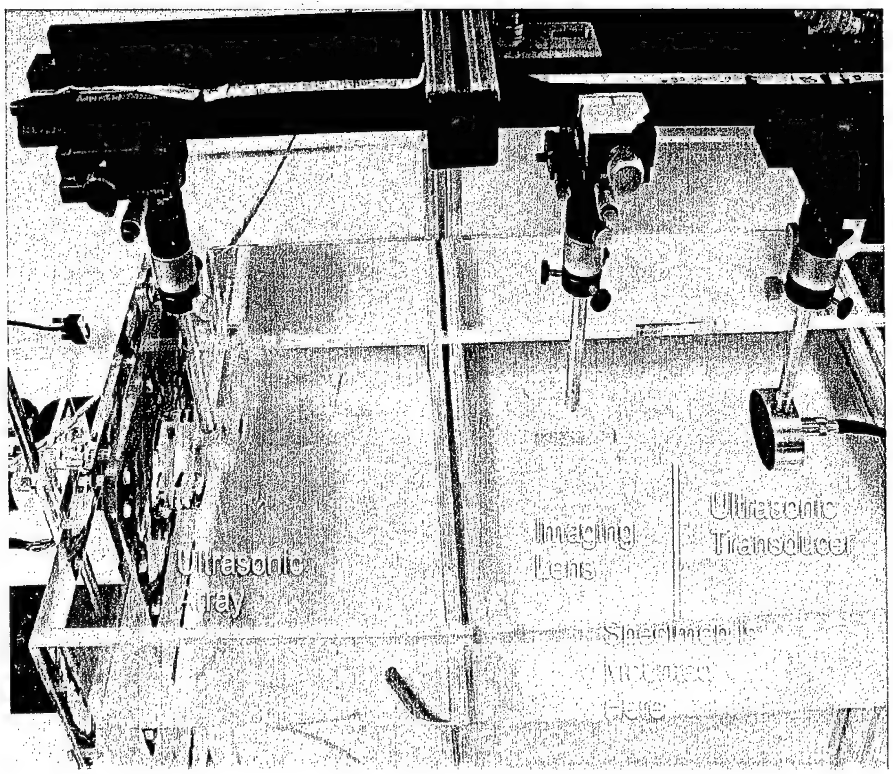
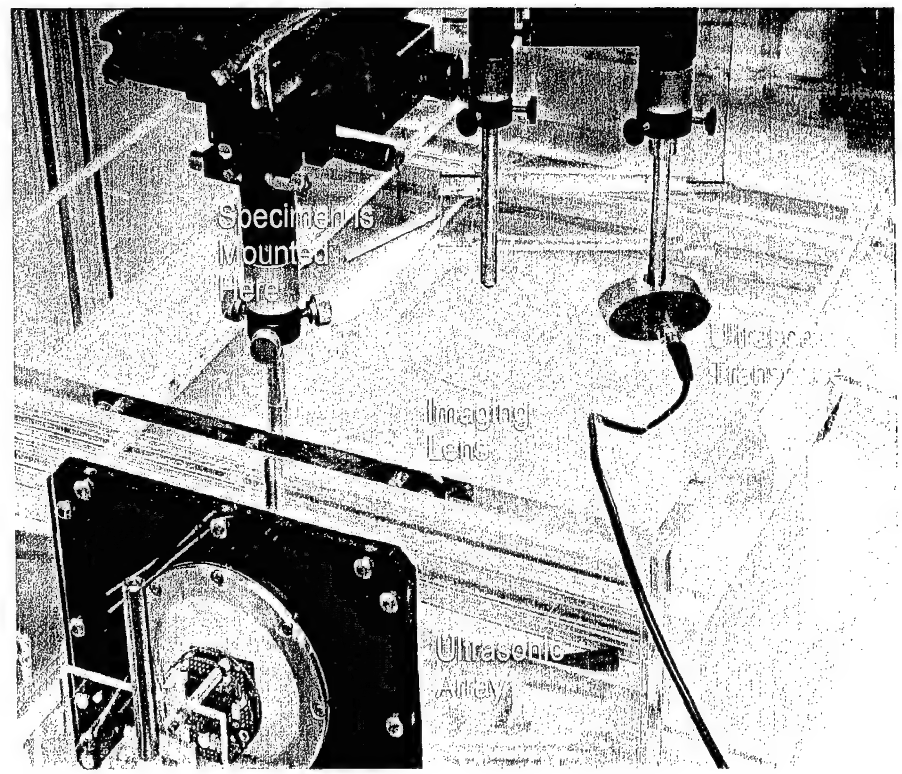
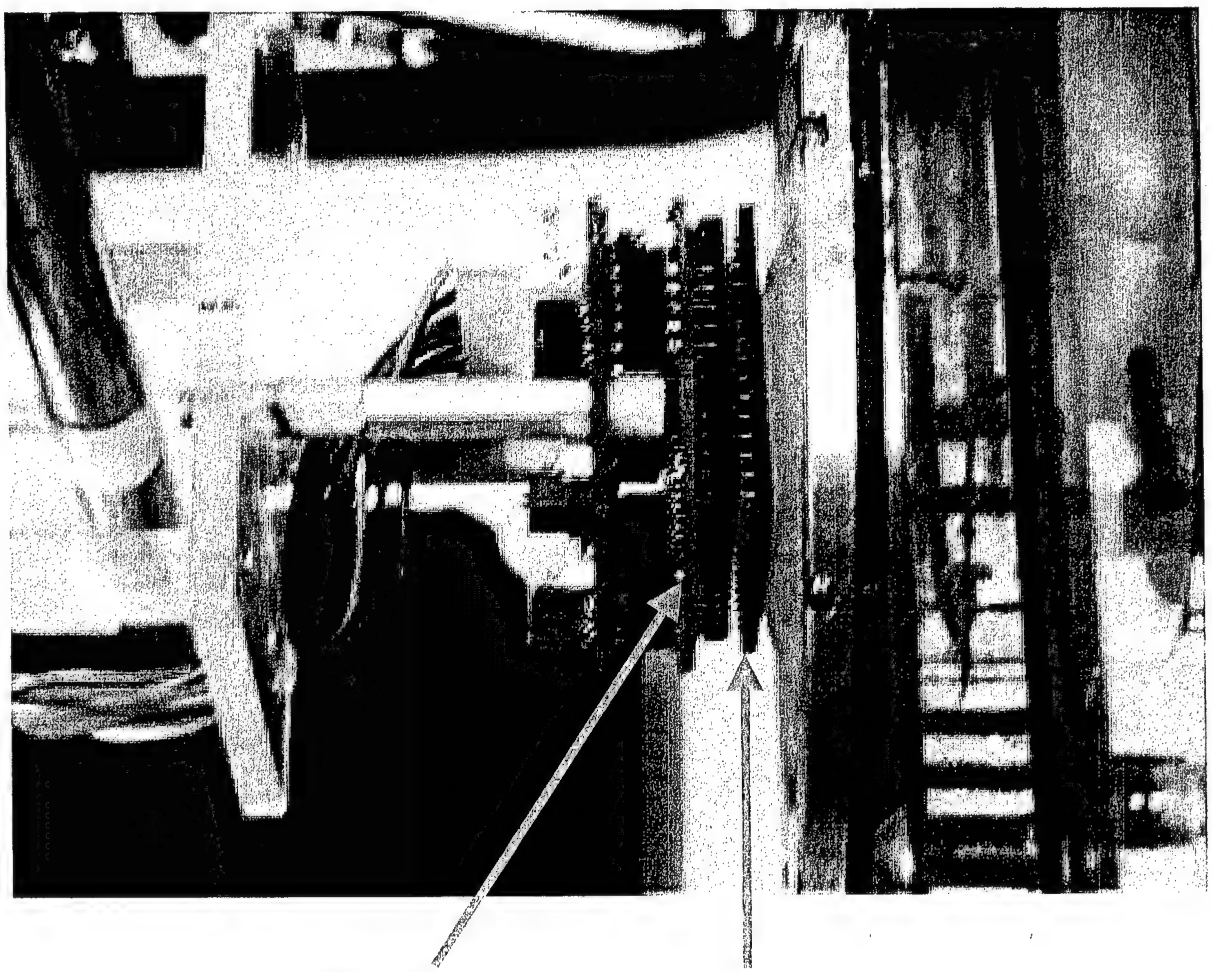
Experimental Apparatus – Through Transmission and Pulse-Echo



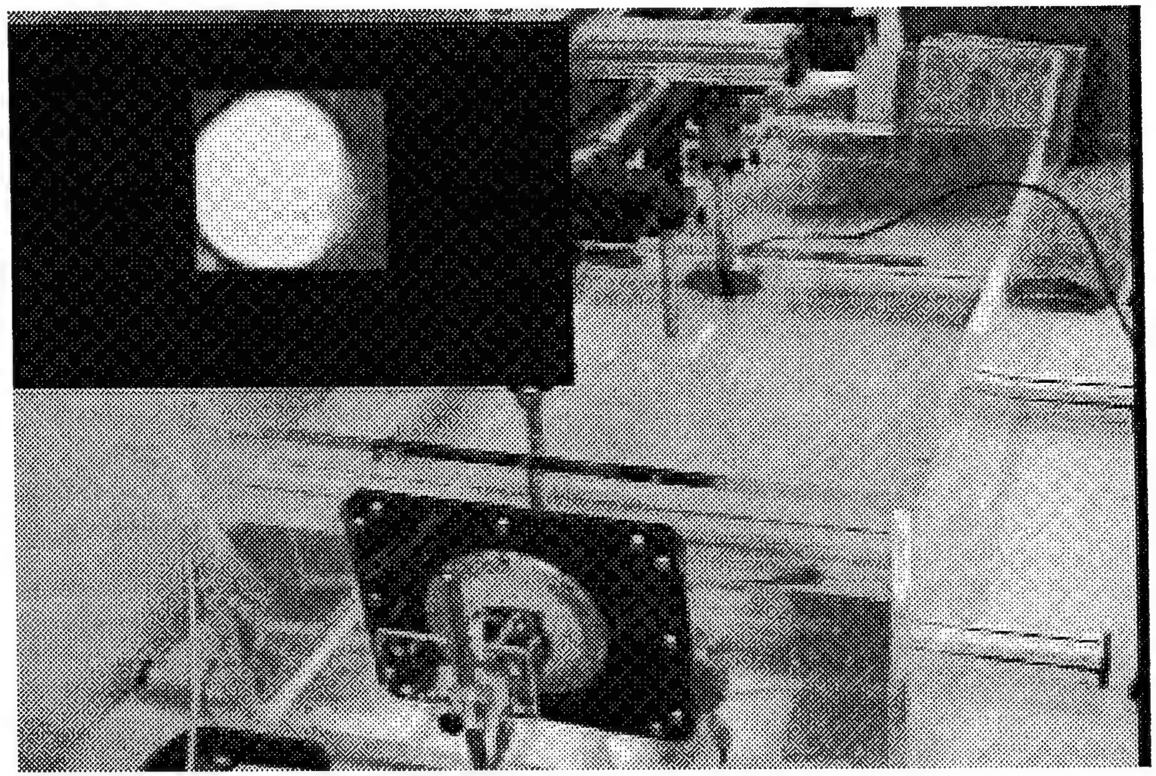


Experimental Apparatus Close-Up



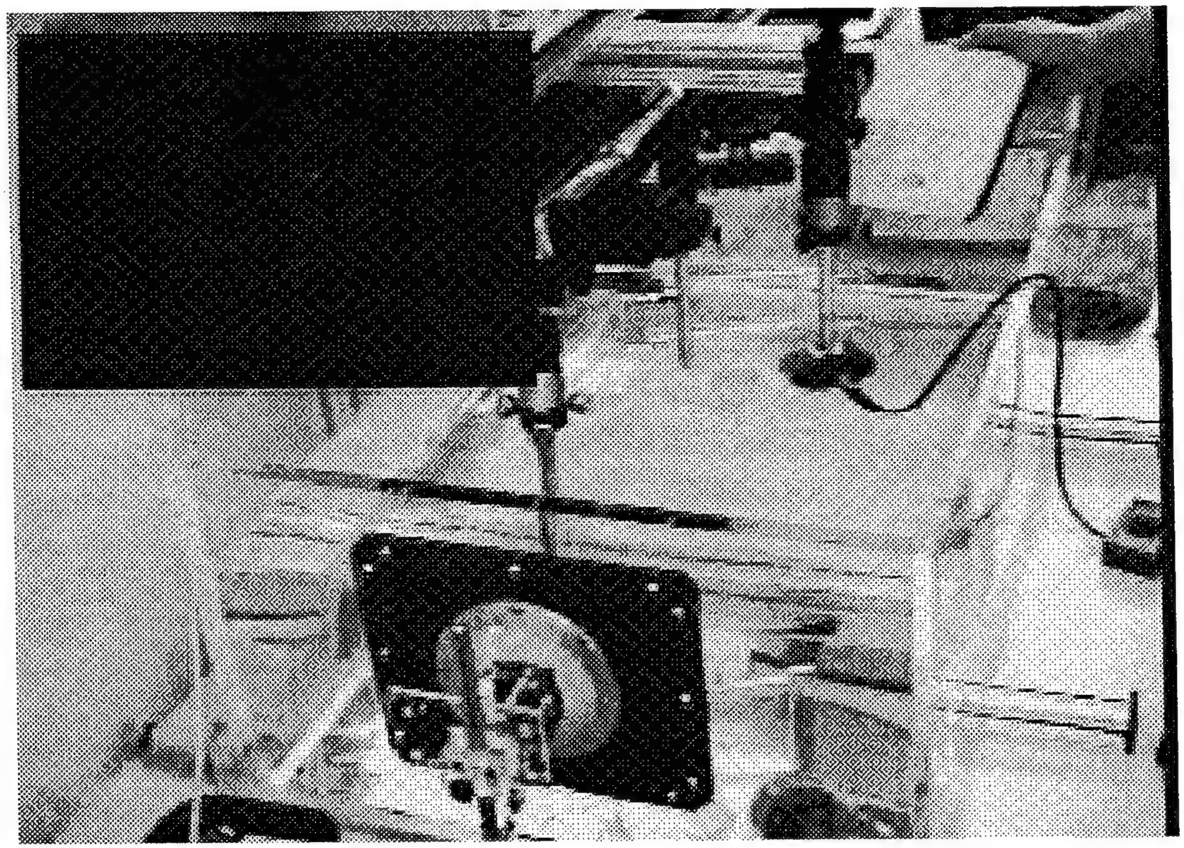
Results – Impact Damage, Through Transmission

- 76.2 mm field of view
- 1 MHz

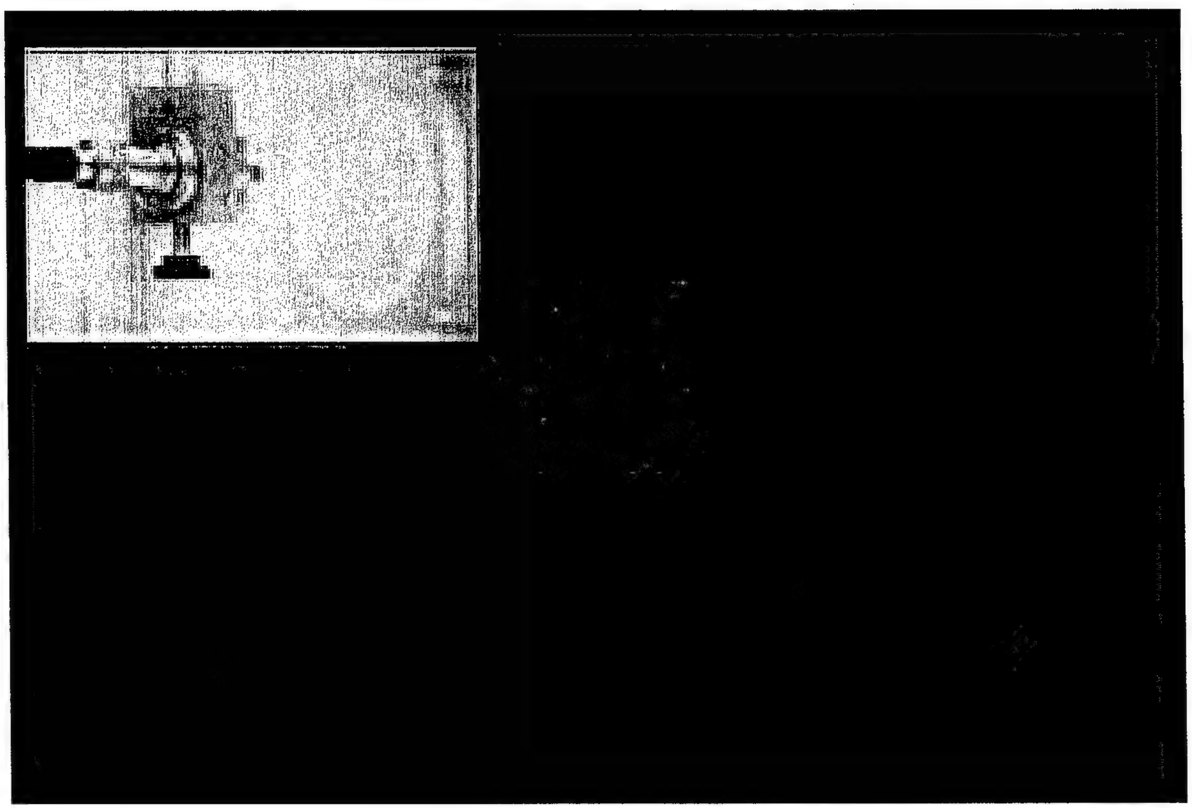


Results – Impact Damage, Pulse-Echo

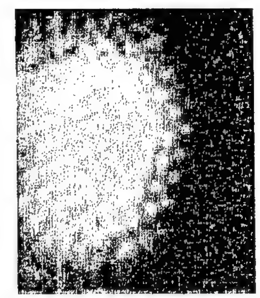
- 76.2 mm field of view
- 1 MHz



Results – Pulse-Echo Fiber Weave Inspection



Fiber weave



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Results on Various Part Geometries

- Can accommodate wide variety of complex shapes
- Investigated flat, angle, channel, TEE, ZEE, and I-beam parts
- Successful on nearly all parts
- Exceptional on radii

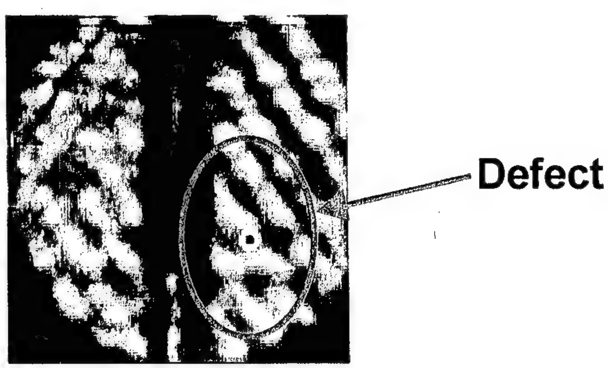
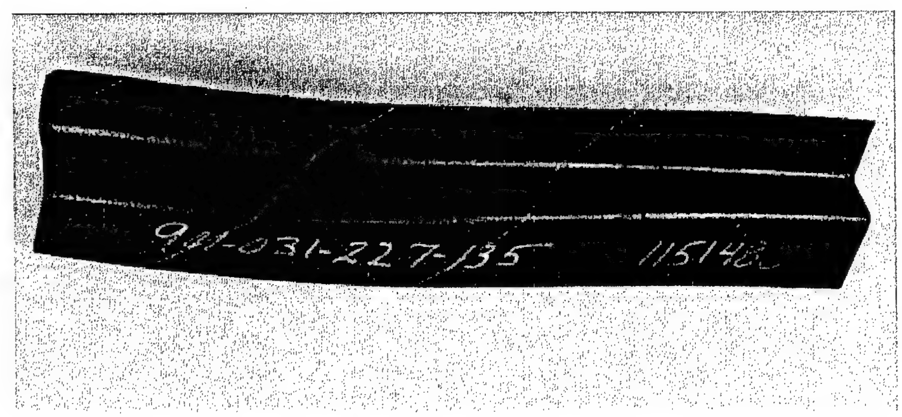
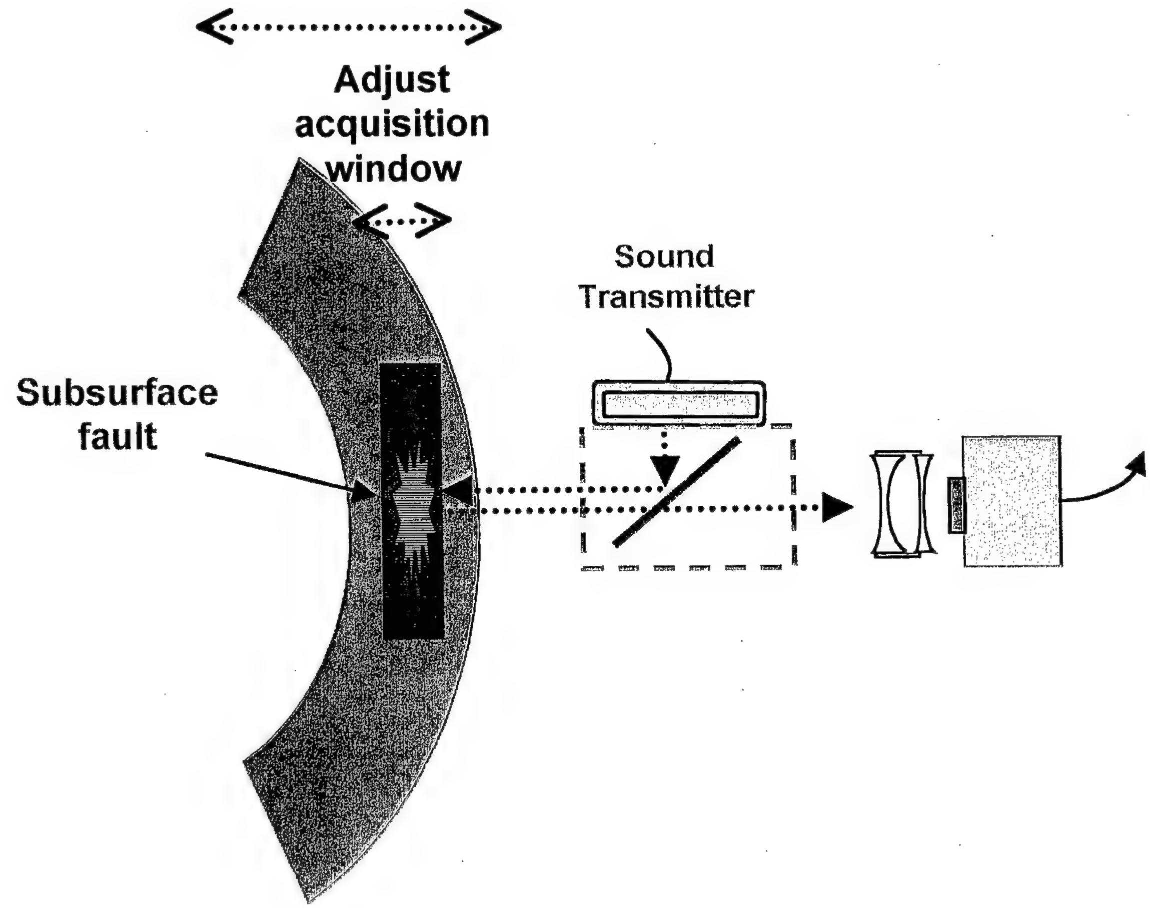


Image of radius

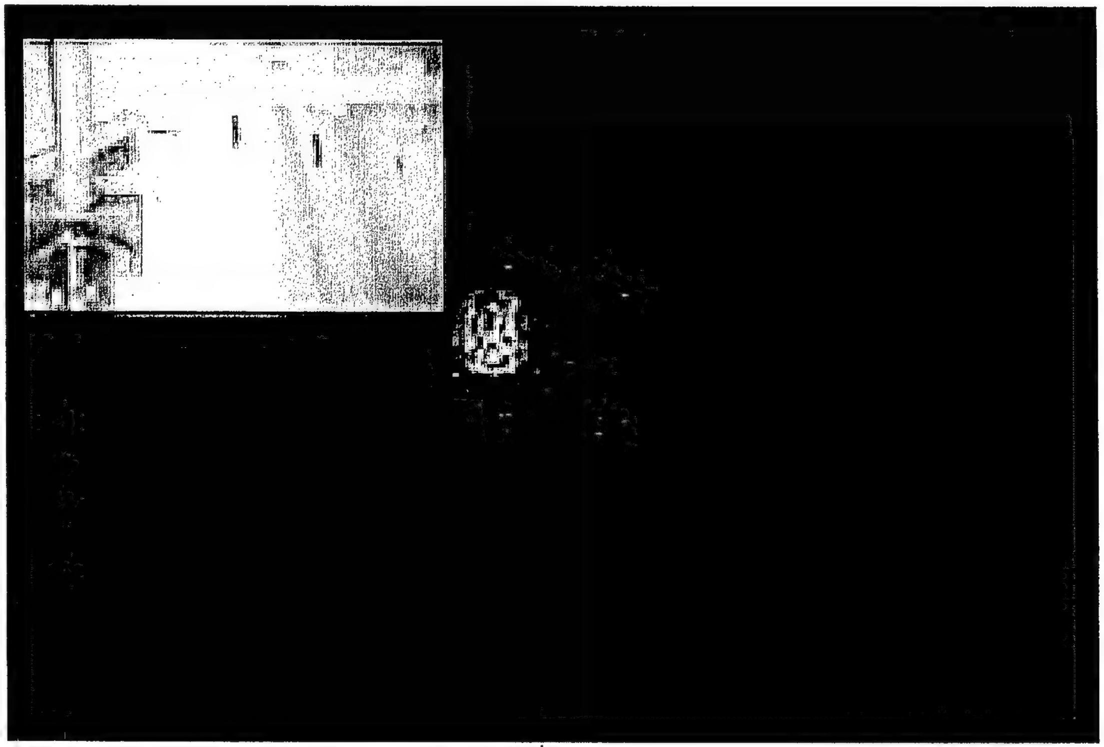


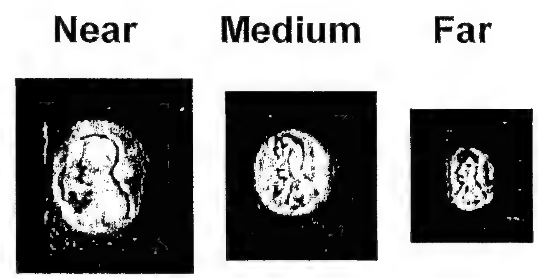
Inspected ZEE-beam

Schematic of Range Gating with Beam Splitter in Pulse-Echo Mode



Pulse-Echo Range Gating on Pennies in Water Tank

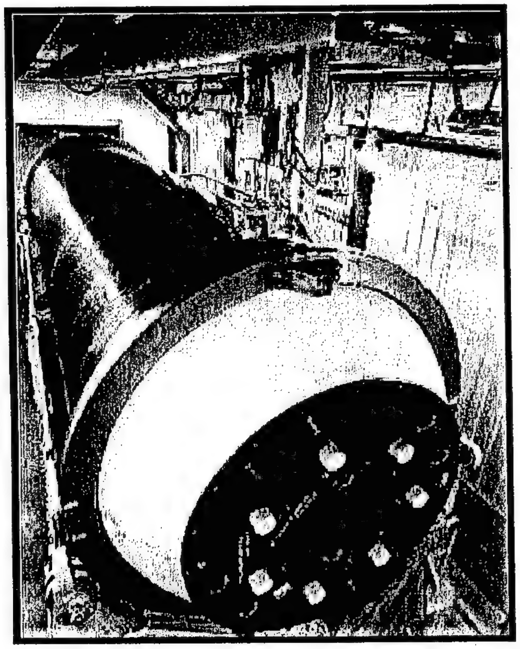




Knife delaminations in Liner/Case Interface

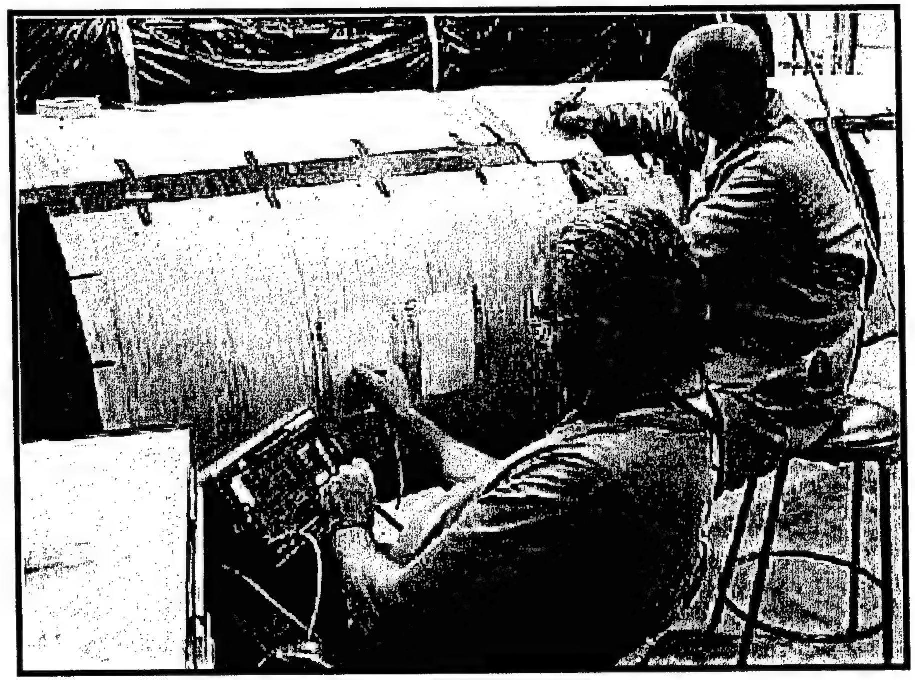
Cost-Saving Applications for New Ultrasonic System

Ultrasonic Inspection of Solid Rocket Motor



0.5 mm pixel with full case coverage requires 16-20 man hours vs. estimated 10 times faster with camera (1-2 hr per segment)

Handheld Mechanical Impedance Inspection of Solid Rocket Motor



Hand testing requires 30-100 man hours per segment (5-6 man crew) and estimated 2-4 hours with camera (crew of 1-2)

Cost Savings

- Time savings per motor = 16 hours (approximate)
- Cost per hour = 2 men x $200/man hr (includes overhead)
- Cost savings per motor = 16 x 2 x $200 = $6400/motor
- ESTIMATE

Time Savings Comparison

Assumptions: 304.8 cm x 304.8 cm (10 ft x 10 ft) sample

Scanning speed of systems: 30.48 cm/s (1 ft/s)

Effective diameter: 0.5 mm (0.002 in.) and 63.5 mm (2.5 in.)

Point-by-Point

- 6096 passes
- 17 hours

Area Scan

- 48 passes
- 8 minutes

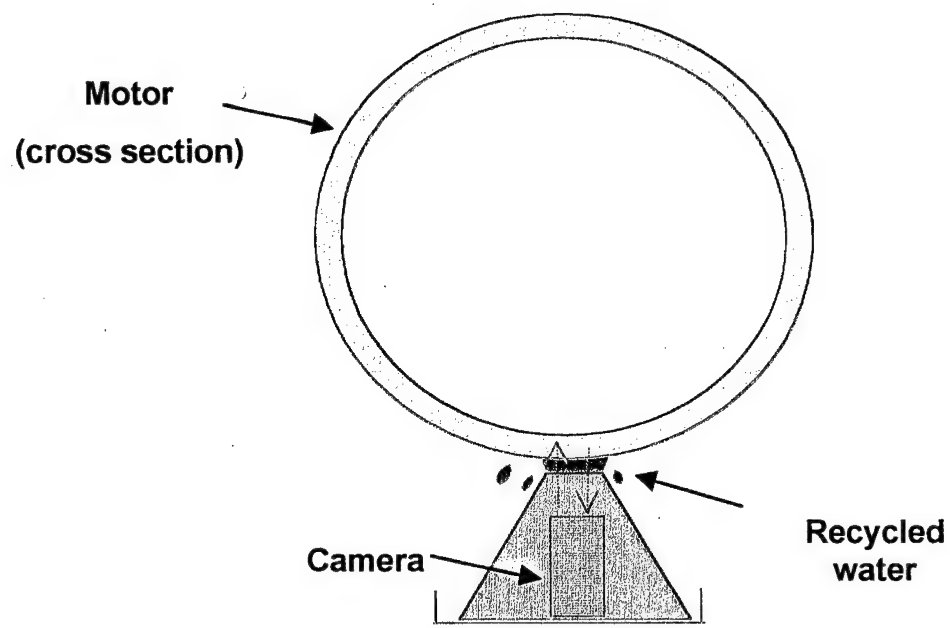
Applications Phase: Objectives and Tasks

Design, build, test and implement a prototype production ultrasound camera system for solid rocket motor inspection.

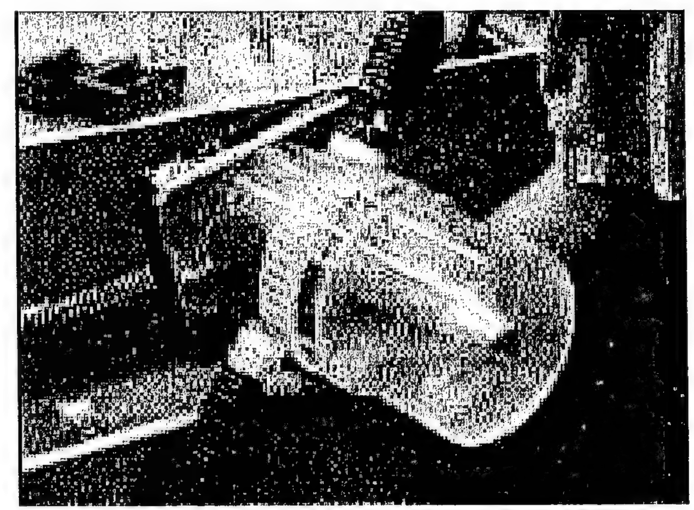
- Establish production system requirements
- Design prototype camera
- Prototype camera fabrication
- Lab test
- Integration
- Production testing

Methods of Coupling System and Specimen

“Volcano”



Squirter



Proposed Automated System Implementation

ULTRA SONIC PLATE WAVE INSPECTION ON OUTSIDE DIAMETER OF GEM-40

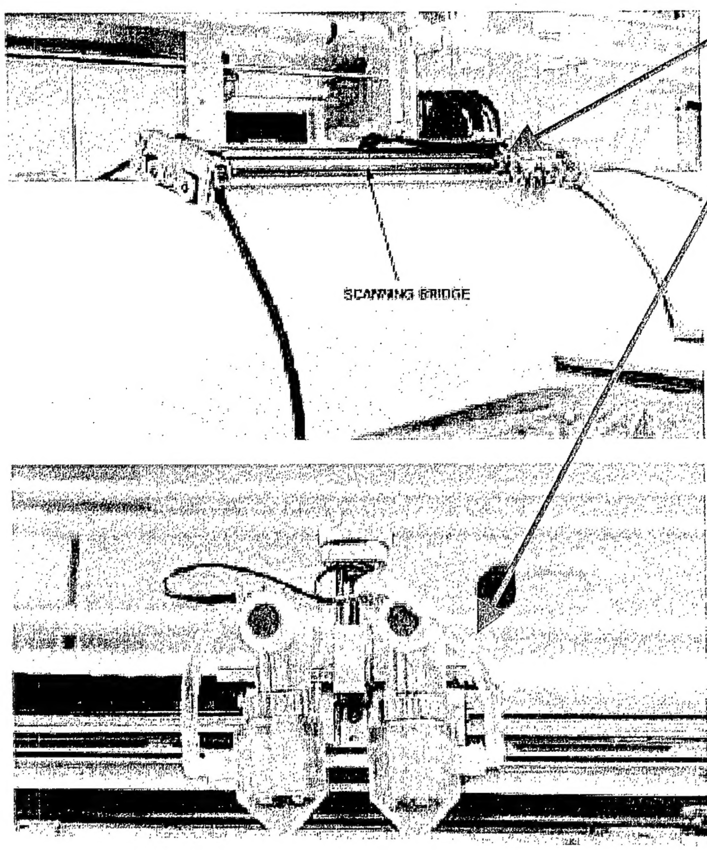


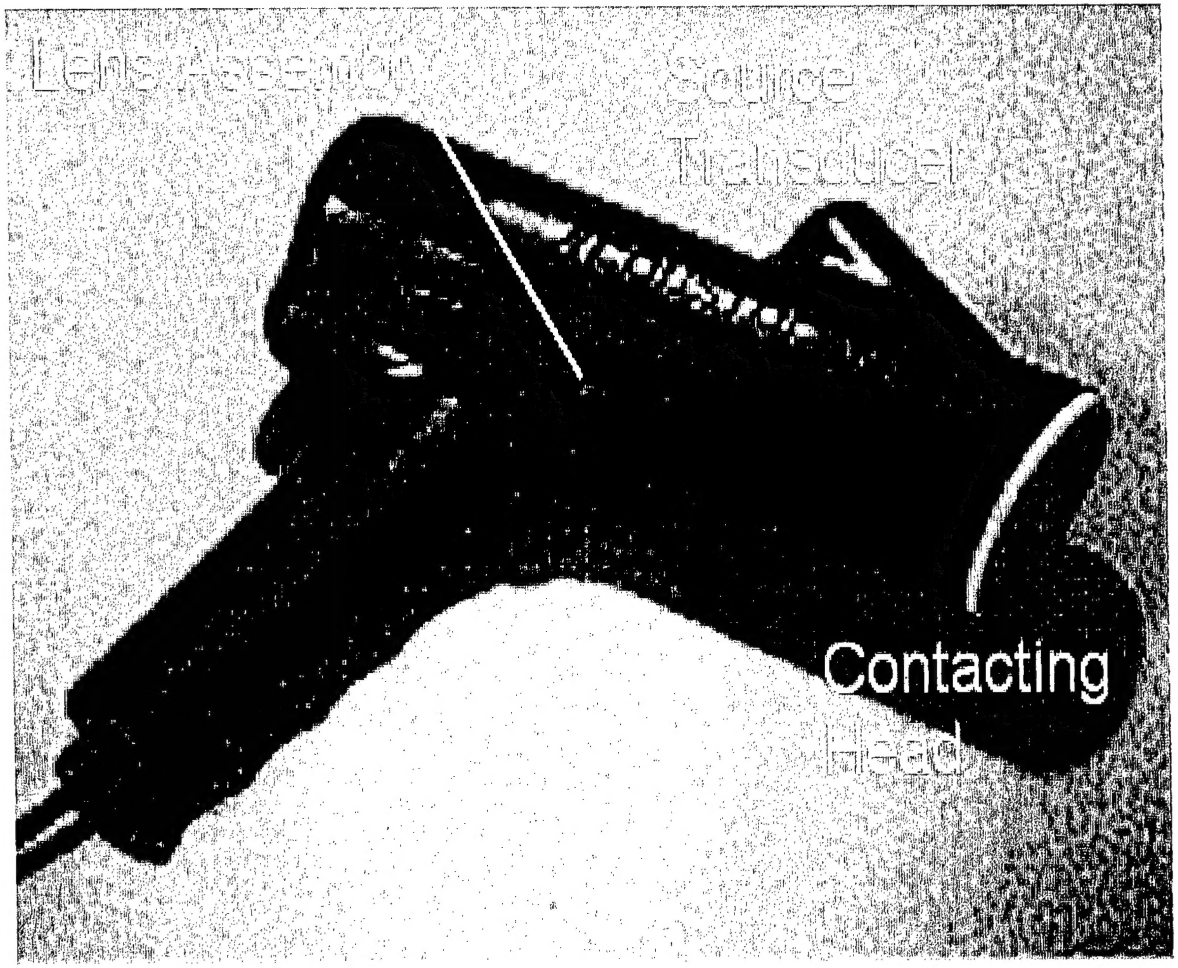
FIGURE D200173A - SONDMAX COMPONENTS

- Modify Sondmax Scanner for Beta Testing - replace Squirter with UT Camera
- Modify Labview Data Acquisition/Control System - adapt for video image
- Scan SRM and Defect Simulate using Baseline System
- Scan using UT camera
- Explore other scan configuration to support inspection of other SRM components (nozzle, interstage, etc.)

Future Work and Other Areas of Application

- Portability
- Other arenas
  - Piping & pressure vessels
  - Semiconductor industry
  - Medical imaging

Other Possible Improvements – Portable System



Summary and Conclusions

- Merging of infrared/ultrasound gives flexible system with enlarged field of view
  - Faster scan
  - Intuitive, real-time inspection
  - Records directly onto videotape
- Solid Rocket Motor Applications
  - Impact damage on GEM
  - Delaminations in case/liner
  - Propellant damage during tensile testing
  - Tactical motors (metal case) inspection
  - Carbon-Carbon composites, zee sections